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Slow Sand Filtration
Influences of Selected Process Variables

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16. ABSTRACT

Biological activity within the sand bed had the strongest influence on removal efficiency of total coliform bacteria by slow sand filtration, as determined by six pilot filters. Temperature, sand bed depth, and sand size also had a strong influence.

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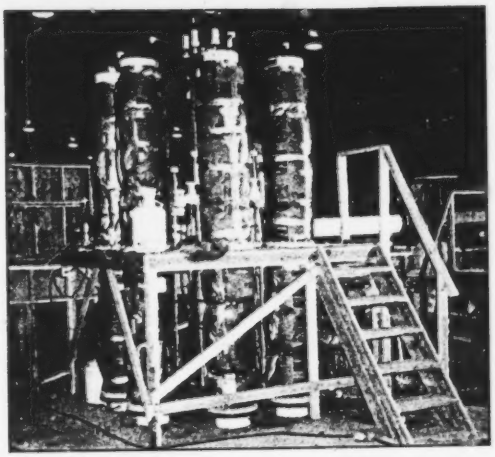

Slow Sand Filtration: Influences of Selected Process Variables

William D. Bellamy, David W. Hendricks, and Gary S. Logsdon

Biological activity within the sand bed had the strongest influence on removal efficiency of total coliform bacteria by slow sand filtration, as determined by six pilot filters (shown above). Temperature, sand bed depth, and sand size also had strong influence.

Research was conducted to determine the influences of selected process variables on the treatment efficiency of slow sand filtration.[1,2] Phase 1 of the research, part of which was published in the February 1985 issue of the JOURNAL,[3] investigated the effects of filter biological aging, schmutzdecke development, and hydraulic loading rate. Process variables of interest were: biological development within the sand bed and its level of activity, temperature, sand size, and sand bed depth. Percent removal of total coliform bacteria was used to evaluate filtration effectiveness and filter response to test conditions. In addition, percent removals of turbidity, *Giardia* cysts, and standard plate count bacteria were used to glean additional information on the effects of different test conditions.

Phase 2 research, which is reported in this article, was influenced by the findings from phase 1, which postulated that the internal biopopulation within the sand bed played a strong role in filtration efficiency. Several questions were raised by the phase 1 research. Could it be stated unequivocally that the high removal efficiencies observed for total coliform bacteria and *Giardia* cysts were due primarily to the development of a biopopulation within the sand bed? Is the level of biological activity in the sand bed important? Can its development be accelerated by adding nutrients? These questions were the impetus for conducting the phase 2 research. Depth of sand, sand size, and temperature were also investigated.

Methods

The approach was to employ physical models of the slow sand filtration process. These were 1-ft- (0.3-m-) diameter filter columns in which one variable was changed and all others were held constant. Filtration efficiencies through the columns were then compared.

Pilot plant

The photograph on page 62 shows the six slow sand filter columns, which were operated continuously for the 11-month phase 2 experiments. A constant-head tank was situated in the center of the filters and distributed equal flow to each one by means of orifices as suggested by Cleasby.[4]

Figure 1 is a schematic of the experimental system.

A cross section of one of the filter units is shown in Figure 2. Effluent flow could be directed through the constant-head outflow device or through a 142-mm membrane filter used for *Giardia* sampling. The cooling element was used to maintain two of the filters at 5°C and 2°C. The feed water to the six filters was maintained at 17°C by means of cooling and heating elements located in the 317-gal (1200-L) feed tank.

Pilot plant operation. The six pilot filters were operated in parallel with a common raw water source. Operating conditions for each filter are given in Table 1.

Three levels of biological activity were studied, along with sand bed depth, sand size, and temperature. Filter 1, the control, had the amount of biological development that would typically occur using Horsetooth Reservoir water. Filter 3 was subjected to 5 mg residual chlorine/L between runs to minimize biological growth. Sterile synthetic sewage, using the formula of Pipes,[5] was added as a nutrient to filter 4 to promote additional biological growth within the sand bed. Filter 2 had a 1.57-ft (0.48-m) sand bed depth (instead of 3.18 ft [0.97 m] for the other filters). Filter 5 was packed with sand having d_{10} size 0.615 mm (instead of 0.287 mm for the other filters). Filters 5 and 6 were operated continuously at 5°C (instead of 17°C for the other filters).

To evaluate the effects of process variables, the filters were spiked continuously with a laboratory culture of total coliform bacteria. Spiking was necessary because the counts were <1 organism per 100 mL in the raw water from Horsetooth Reservoir. Filter 3, which was disinfected by a sodium hypochlorate solution, was purged of disinfectant with sodium thiosulfate prior to the tests. Effluent samples from the six filters were obtained once a day during the test period. This series of measurements, together with the spiking, constituted a test run. Runs were conducted at various times, usually weekly, throughout the 11-month continuous filter operation. The imposed influent concentration of total coliform bacteria ranged from 2 to 280 000 colonies/100 mL. The influent concentration was held relatively constant during a test run but varied between runs. Sewage was not used as a source of coliforms because the debris and nutrients could have interfered with the testing.

In addition to the total coliform testing, removals of turbidity and standard plate count bacteria were monitored routinely. Some test runs were made by spiking with cultured standard plate count bacteria at several orders of magnitude above ambient levels.

Tests with *Giardia* cysts, concentrated from dog feces, were conducted on a more limited basis because the addition of cysts resulted in debris being added to the filter. The first test was conducted after nine weeks of operation. A total of 21 tests of several days' duration was conducted using *Giardia* cysts.

The time to terminal head loss was not determined for the Horsetooth Reservoir water source. It was estimated

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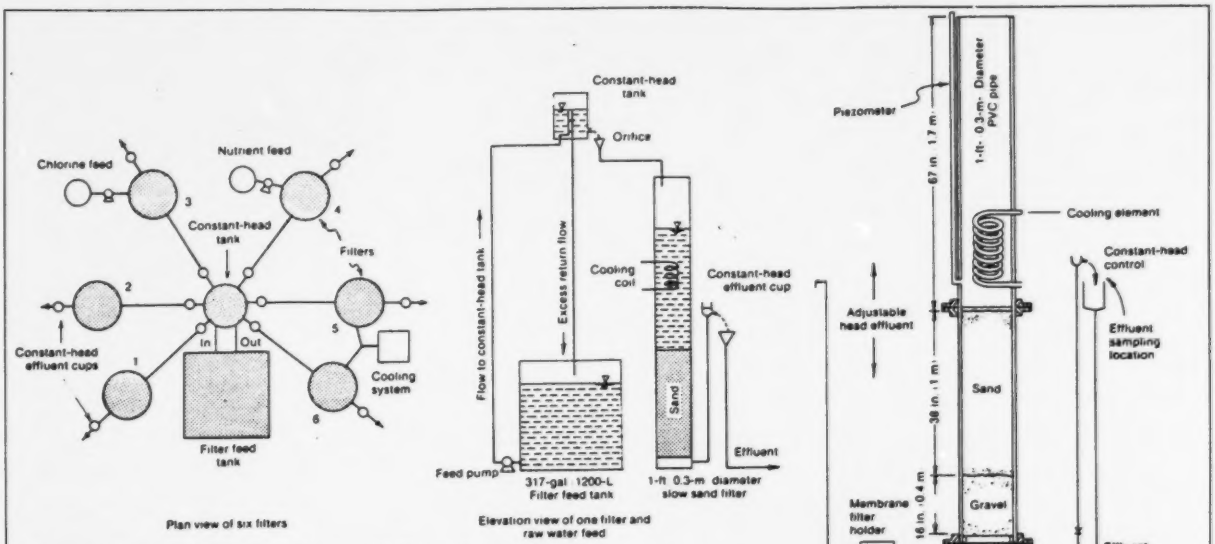

Figure 1. Flow schematic of slow sand filter pilot plant

Figure 2. Cross-section drawing of 1-ft (0.3-m) slow sand filter column

TABLE 1

Operating conditions for phase 2 experiments—February 1983 to December 1983

Condition	Variable of Interest					
	Control Filter 1	Sand Bed Depth Filter 2	Disinfection* Filter 3	Nutrients Added Filter 4	Sand Size Filter 5	Temperature Filter 6
Hydraulic loading rate—*gpm/sq ft (m/h)*	0.05 (0.12)	0.05 (0.12)	0.05 (0.12)	0.05 (0.12)	0.05 (0.12)	0.05 (0.12)
Sand bed depth—*ft (m)*	3.18 (0.97)	1.57 (0.48)	3.18 (0.97)	3.18 (0.97)	3.18 (0.97)	3.18 (0.97)
Sand size, d_{10}—*mm*	0.29	0.29†	0.29*	0.29	0.62	0.29
Sand uniformity coefficient	1.5	1.5	1.5	1.5	1.6	1.5
Temperature—°C	17	17	17	17	5‡	5§
Nutrient loading**	0	0	0	5	0	0
Disinfection—*mg Cl/L*	0	0	5**	0	0	0

*A solution of NaOCl was metered continuously between test runs to this filter, and a 5-mg/L chlorine residual was maintained. Disinfection was terminated Aug. 14, 1983, and the filter column was filled with 0.128-mm sand to conduct an experiment with another sand size.
†Filter 2 was filled with sand to 3.18 ft (0.97 m), and a surface deposit with diatomaceous earth (Manville C-545) at 3 kg/m² was placed on the filter Aug. 14, 1983.
‡Filter 5 was operated at 17°C beginning Aug. 14, 1983.
§The water temperature of filter 6 was lowered to 2°C beginning Aug. 14, 1983.
**A solution of sterile synthetic sewage was metered continuously to filter 4, resulting in a BOD loading of approximately 4 mg/L.

that this would take from several months to a year, depending on the operating conditions. Test runs were conducted during the continuous operation of the filters. The schmutzdecke was removed from the filters as needed in accordance with testing requirements and not because of high head losses.

Results and discussion

***Giardia* removal.** Results of the phase 2 *Giardia* removal tests, shown in Table 2, demonstrate that removal was not affected by increasing the effective sand size to 0.615 mm, by continuous operation at 5°C, or by reducing the sand bed depth to 1.57 ft (0.48 m). Each filter in Table 2 had a mature biological population and had the same influent water for runs 1, 2, and 3, respectively, and was operated at a hydraulic loading rate of 0.05 gpm/sq ft (0.12 m/h). Cysts were not detected in any effluent samples.

In an attempt to induce cyst breakthrough, another filter column was freshly packed with 0.615-mm sand, operated at 0.19 gpm/sq ft (0.47 m/h), and then challenged during the first two days of operation with 2770 cysts/L. This test resulted in 26 cysts/L passing through the filter. Even under these extreme conditions, removal was 99 percent. Testing with new sand was carried out also during rapid sand experimentation.[6] Testing with 0.43-mm sand at hydraulic loading rates in excess of 6 gpm/sq ft (14 m/h) and without chemical addition resulted in four of eight test runs having less than 50-percent removal. These results and those obtained during the slow sand testing demonstrated that the hydraulic loading rate did affect *Giardia* removal for columns packed with new sand. Cyst removal was not perceptibly affected by the hydraulic loading rate within the normal slow sand operating ranges of 0.02–0.16 gpm/sq ft (0.04–0.4 m/h) when the filter had a mature biological population.

Determining the effects of process variables on filter performance. The effects of process variables on the performance of the slow sand filter were evaluated using percent removals of total coliform bacteria or turbidity as the measure of efficiency.

Biological community. The previously reported phase 1 results demonstrated that the state of the biological community within the filter significantly influenced filter effectiveness. Percent removals of total coliform bacteria were greatest (e.g., 97.6–99.996 percent) when the filter had a mature biological population. These removals decreased by a factor of 10–100 after removal of the schmutzdecke and replacement of the sand, respectively.

Based on these results, the phase 2 investigations were designed to study the effect of low, natural, and accelerated biological activity on filter performance. For the low biological activity condition, growth was prevented in filter 3 by

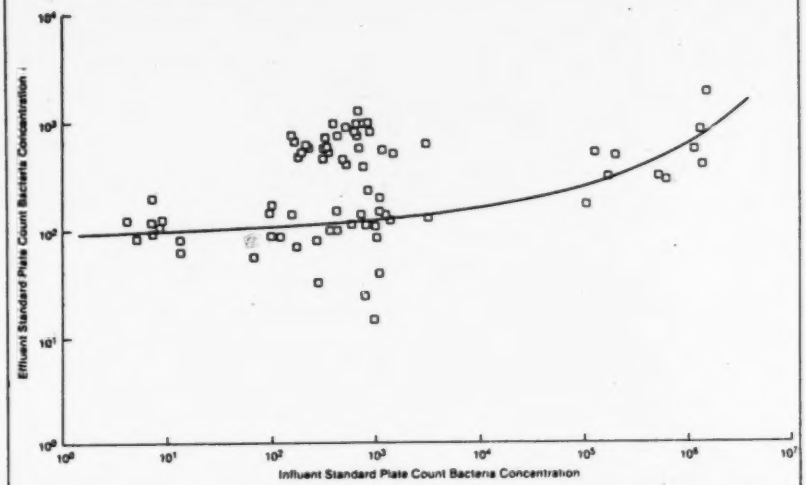

Figure 3. Influent versus effluent standard plate count bacteria concentrations for slow sand filtration *(values obtained from a mature filter operated with an effective sand size of 0.297 mm, at a hydraulic loading rate of 0.12 m/h [0.05 gpm/sq ft] and at a temperature of 17°C)*

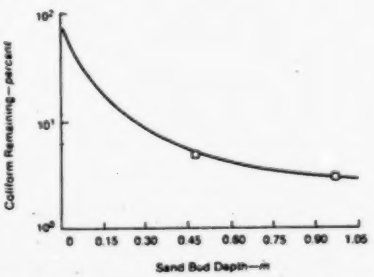

Figure 4. Effect of sand bed depth on percent remaining of total coliform bacteria in effluent during slow sand filtration *(the two plotted points are averages of 164 coliform analyses for each point; hydraulic loading rates were 0.12 m/h [0.05 gpm/sq ft], and sand bed depths were 3.18 ft [0.97 m])*

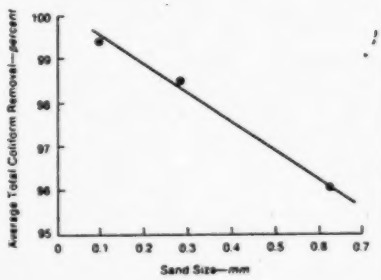

Figure 5. Effect of sand size on removal of total coliform bacteria for slow sand filtration, phase 3 testing *(each point is an average of results from 18 test runs for each filter; hydraulic loading rate was 0.12 m/h [0.05 gpm/sq ft], and sand bed depths were 3.18 ft [0.97 m])*

TABLE 2

Effect of sand bed depth, sand size, and temperature on Giardia *removal by slow sand filtration—all filters operated at 0.05 gpm/sq ft (0.12 m/h) hydraulic loading rate*

Filter Designation	Test Run Number	Influent Cyst Concentration *cysts/L*	Cysts Detected In Effluent *number*	Detection Limit *cysts/L*	Removal* *percent*
Filter 1—Control†	1	3000	0	0.42	>99.99
	2	1956	0	1.33	>99.93
	3	1845	0	1.18	>99.94
Filter 2—with 1.57-ft (0.48-m) sand bed depth	1	3000	0	0.43	>99.99
	2	1956	0	1.33	>99.93
	3	1845	0	1.08	>99.94
Filter 5—with 0.615-mm sand,‡ operated at 5°C	1	3000	0	0.47	>99.98
	2	1956	0	1.48	>99.92
	3	1845	0	1.05	>99.94
Filter 6—operated at 5°C	1	3000	0	0.34	>99.99
	2	1956	0	1.48	>99.92
	3	1845	0	1.33	>99.93

*Percent removal based on detection limit

†The control filter was operated at 14°C with an effective sand size of 0.28 mm and a sand bed depth of 3.18 ft (0.97 m); the uniformity coefficient of the sand was 1.53 for filters 1, 2, and 6.

‡Sand size is the d_{10} size; the uniformity coefficient was 1.6.

chlorinating at 5 mg chlorine residual/L between test runs and dechlorinating with sodium thiosulfate prior to a test run. An augmented biological activity condition was created in filter 4 by continuously adding sterile synthetic sewage to the filter. The synthetic sewage formula was added in sufficient quantity to reduce the dissolved oxygen across the filter by 3–4 mg/L. Filter 1, a control filter representing the natural condition, used unaltered raw water from Horsetooth Reservoir.

The results of the phase 2 testing, shown in Table 3, demonstrate that as the activity of the biological community increased (i.e., from minimal biological community for the chlorinated filter to augmented activity for the nutrients-added filter), the percent removals of coliforms, standard plate count bacteria, and turbidity increased significantly. These results demonstrate the unmistakable influence of biological activity on filter performance.

The variation in turbidity removal is especially interesting, because it may offer some insight into the removal of inorganic particulate matter, such as clays. Raw water turbidity of Horsetooth Reservoir water averaged from 6 to 8 ntu, and filtered water turbidity ranged from 3 to 5 ntu. Concentrations of microorganisms in the raw and filtered water were too low to cause the observed levels of turbidity. Concentrations of standard plate count bacteria in Horsetooth Reservoir water are typically less than 200/100 mL, and total coliform bacteria often cannot be detected. Also, the nutrient levels in Horsetooth Reservoir water are extremely low. An X-ray analysis with a scanning electron microscope of residue on membrane filters[7] led to the suggestion that clay particles, especially kaolinite and montmorillonite, might be causing the high turbidity in the filtered water.

Filtering a sample of raw water through a series of membrane filters with pore sizes of 8, 5, 1.2, 0.45, and 0.22 μm resulted in turbidity removals of 1, 2, 35, 75, and 85 percent, respectively, which attests to the small sizes of the colloids comprising the turbidity.

These results show the importance of biological action, even for removal of inorganic particles. Huisman and Wood[8] reported that the sticky gelatinous film on the surface of the schmutzdecke caused inert matter to be held until the schmutzdecke was removed. Based on the results of this study, the production of exocellular polymers by the microorganisms attached to the sand particles within the sand bed also appears to be probable. Pavoni et al[9] reported that exocellular polymers produced by activated-sludge-type bacteria could flocculate kaolinite suspensions and promote settling. It is speculated that the en-

hanced turbidity removal observed in the nutrients-added filter could have been caused by higher levels of production of exocellular polymer.

Influent bacteria concentration. Previously reported results demonstrated that increasing concentrations of influent coliform bacteria and standard plate count bacteria caused increased percentages of removal and, at the same time, corresponding increases in effluent concentrations. The standard plate count results also showed that negative removals (e.g., concentrations in the effluent exceeded concentrations in the influent) could and did occur when the influent concentration dropped below approximately 1000 colonies/mL.

This latter characteristic was studied in more detail during the second phase of testing by increasing the influent standard plate count concentration to more than 100 000 colonies/mL for 11 days and decreasing the concentration to less than 10 colonies/mL for 10 days. Figure 3 is a plot of the influent versus effluent concentrations for this testing. The curve, representing the trend in the data, indicates that the effluent standard plate count bacteria concentration is independent of the influent concentration over an influent range from 1 to approximately 1000 colonies/mL. This effluent level may be designated as a "base level" concentration. It consists primarily of bacteria being grown and sloughed by the filter and is not significantly influenced by low levels of influent bacteria. The data also indicate that large influent concentrations are required before an increase in the effluent level is noticeable. In other words, the internal biopopulation of the sand bed seems to metabolize the convected microorganisms until its capacity is exceeded. At this time, some of the influent organisms will pass through the filter. Unless the filter is subject to loadings from a concentrated source such as sewage, it is not likely that the capacity of the base level of bacteria to metabolize will be overwhelmed. Thus, these results are explained by the idea that a slow sand filter is a biological system that undergoes a series of events: (1) removal within the sand bed, (2) adsorption of convected bacteria on the biofilm attached to sand grains, (3) metabolism of convected bacteria, and (4) synthesis of attached bacteria.

Temperature. Table 4 shows that decreasing the temperature from 17°C to 5°C or 2°C will decrease both removals of coliform bacteria and removals of standard plate count bacteria from about 99 to 90 percent nominally. The standard plate count results were obtained during the period when the influent to each filter was being spiked with approximately 5×10^5 colonies/mL. The filtration efficiency was not reduced as sharply as reported in the literature.[8,10] The latter results, however, appeared to be from series testing that compared seasonal changes and not from parallel testing with identical influents. Burman[11] reported *Escherichia coli* and coliform reductions of 41 and 88 percent during February (1956) for a full-scale filter compared with 99 percent during the rest of the year.

TABLE 3

Effect of the biological community on percent removals of total coliform bacteria, standard plate count bacteria, and turbidity—filters 1 and 4 were biologically mature

Parameter	No Biological Community—Filter 3* *percent removed*	Ambient Activity, i.e., Control—Filter 1 *percent removed*	Augmented Biological Activity—Filter 4† *percent removed*	Number of Samples *percent removed*
Total coliform	60.1	97.5	99.9	24
Standard plate count	-89	-41	58	23
Turbidity	5	15	52	26

*Filter 3 was chlorinated between test runs.
†Nutrients were added continuously to filter 4.

TABLE 4

Two comparisons showing the effect of temperature on percent removals of total coliform bacteria and standard plate count bacteria—filters were biologically mature

Parameter	Control Filter 1 17°C *percent removed*	Cold Filter 6 5°C *percent removed*	Number of Samples	Control Filter 1 17°C *percent removed*	Cold Filter 6 2°C *percent removed*	Number of Samples
Total coliform	97	87	82	99.6	92	9
Standard plate count				99.9	90	10

TABLE 5

Standard plate count bacteria removal as affected by sand size, phase 3 testing; filter 1 was the control; bacteria concentrations are geometric means

Parameter	Filter 1 Sand Size—0.278 mm	Filter 5 Sand Size—0.615 mm
Number of samples	10	10
Influent concentration average standard plate count—*number/mL*	469 000	469 000
Effluent concentration average standard plate count—*number/mL*	470	1050
Percent removal	99.9	99.7

Sand bed depth. The trend line shown in Figure 4 illustrates a relationship showing the percentage of total coliform bacteria remaining in the effluent as affected by bed depth. The trend shows that the percentage of coliforms remaining declines with increasing sand bed depth. The line is anchored at 100 percent remaining at a 0.0-ft (m) bed depth to show the probable trend. The two plotted points, having values of 3 and 5 percent remaining, were statistically different according to analysis of variance at a 99.8-percent significance level ($p = 0.002$). In other words, the 2-percent difference in treatment efficiency is real and the trend shown does exist. The relationship shown indicates that bacterial removal is not overly sensitive to sand bed depths in excess of 1.57 ft (0.48 m). In practice this means that a series of schmutzdecke removals, with the resulting attrition of the sand bed from 3.2 to 1.6 ft (1 to 0.5 m), will not seriously impair the efficiency of the filtration process.

Sand size. To better discern the role of effective sand size, three filters were packed with sand having effective sizes 0.62, 0.28, and 0.13 mm. Eighteen test runs using cultures of *E. coli* (coliform) bacteria were then conducted parallel with each filter in what was designated as phase 3 testing. Each of these filters had a mature biological population. Figure 5 shows the results of the phase 3 tests, indicated by the plotted points.

The data show that an increase in treatment efficiency occurs with a decrease in sand size. Coliform removal improved from 96.0 to 98.6 to 99.4 percent for effective sand sizes of 0.615, 0.278, and 0.128 mm, respectively. Each plotted point represents an average of results from 18 test runs for each filter.

Table 5 indicates a similar trend for standard plate count bacteria removal for 10 samples. With a spiked influent of approximately 5×10^5 colonies/mL, the 0.278-mm sand allowed only 470 colonies/mL to pass, whereas the 0.615-mm sand allowed 1050 colonies/mL to pass.

Removal mechanism. The experimentally derived relationship shown in Figure 5, i.e., increasing percentages of removal of coliform bacteria with decreasing sand size, stimulated conjecture about the removal mechanism. Straining and adsorption were considered plausible, and each is consistent with Figure 5. To ascertain whether straining was

important, another experiment was performed in which a 5-mm depth of diatomaceous earth (d_{10} = 0.013 mm) was deposited on the surface of one of the 1-ft- (0.3-m-) diameter sand beds packed with sand of d_{10} = 0.28 mm. The column had already been operated for more than 100 days to mature the bed, and was operated for 40 more days to develop and mature the schmutzdecke, similar to the control filter and the filter using the 0.128-mm sand. Six tests were done to determine removals of coliform bacteria. Removals averaged 98.5 percent, vis-a-vis 97.7 percent for the control, and 99.4 percent for the 0.128-mm sand. If the removal mechanism was straining, the removal of coliform bacteria should have approached 100 percent (extrapolating the relationship of Figure 5 to the d_{10} size of the diatomaceous earth). Since the percent removal was only 98.5 percent, vis-a-vis 99.4 percent for the d_{10} = 0.128-mm sand bed, the hypothesis that straining is a removal mechanism was not supported. The hypothesis that adsorption is an important removal mechanism is supported by the relationship shown in Figure 5, because higher removals would be expected with the larger surface area of the smaller sand size.

Summary

The phase 2 research corroborated the major finding of phase 1; i.e., biological activity within the sand bed is an important factor in parameter removal efficiency. Also, the phase 2 research delineated the influences of temperature, sand bed depth, and sand size on filtration efficiencies for total coliform bacteria.

Temperature. The phase 2 experiments for mature filters showed that *Giardia* removals were uniformly 100 percent for continuous operation at both 17° and 5°C. Removals of total coliform bacteria, however, declined from 97 percent at 17°C to 87 percent at 5°C. Effluent concentrations of standard plate count bacteria were 100 times higher at 2°C than at 17°C. The two latter tests demonstrate the sensitivity of the slow sand filtration process to the effects of low temperatures.

Sand bed depth. Coliform removals averaged 97 percent for the control filter with a bed depth of 3.18 ft (0.97 m), and declined only to 95 percent for the filter with a bed depth of 1.57 ft (0.48 m). These results demonstrate that the bed depth can be reduced to 1.57 ft (0.48 m) by repeated schmutzdecke removals without significant impairment of filtration removal efficiency.

Sand size. Removals of *Giardia* cysts were 100 percent for all sand sizes tested. Removals of total coliform bacteria declined from 99.4 percent for 0.128-mm sand to 96.0 percent for 0.615-mm sand size. Standard plate count bacteria concentrations in slow sand filter effluent increased from 470 organisms/mL for 0.287-mm sand to 1050 organisms/mL for 0.615-mm sand.

Even though the results showed that sand size had a functional influence on bacteria removals, the percent removals were still high with 0.615-mm sand. So, from the standpoint of removal effectiveness, the argument for using smaller sand is not strong. From an economic viewpoint, however, the argument supports an effective sand size of about 0.35 mm. Huisman and Wood[8] found that the schmutzdecke will penetrate to a greater depth with larger sand, necessitating the removal of 3 to 10 times more sand (e.g., 1 to 4 in. [3 to 10 cm]) during schmutzdecke removal. Removal of larger amounts of sand increases operating costs. This supports using the smaller size when there is an economically favorable choice.

Biological activity. Phase 2 results showed that the average coliform removals for filter 3, which was chlorinated between test runs and had no biological community, were only 60 percent, whereas the average coliform removal was 98 percent for the control filter. Filter 4, which had nutrients added, showed an average coliform removal of 99.9 percent. The results of the phase 2 tests augment those of phase 1, establishing unequivocally the importance of the biological community and its level of activity within the sand bed.

Conclusions

From the results of this research it may be asserted that slow sand filtration is an effective water treatment technology, as determined by removals of total coliform bacteria and *Giardia* cysts. Further, the process is "passive" in nature, requiring little maintenance on the part of the operator. This technology should be considered during the selection of a water treatment system. Pilot-plant testing should be done, however, to determine the technical feasibility of each alternative. Selection should be determined by economic analyses in addition to the appropriateness of the technologies for the community at hand.

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About the authors: *A graduate of Colorado State University (PhD) and of the University of Wyoming (BS and MS), William D. Bellamy is currently a sanitary engineer with CH2M Hill, 1301 Dove St., Suite 800, Newport Beach, CA 92660. The research for this article spanned a three-year period and included rapid sand and diatomaceous earth filtration investigations. Bellamy is a member of AWWA, WPCF, and ASCE, and has had his work published previously in* Journal AWWA. *David W. Hendricks is a professor in the Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523, and Gary S. Logsdon is a research sanitary engineer, Drinking Water Research Division, Municipal Environmental Research Laboratory, US Environmental Protection Agency, 26 W. St. Clair St., Cincinnati, OH 45268.*

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